

# **North Pacific Acoustic Laboratory: Analysis of Shadow Zone Arrivals and Acoustic Propagation in Numerical Ocean Models**

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## **LONG-TERM GOALS**

My long-term goal is a complete and thorough understanding of the properties of acoustic pulses sent over megameter scales. In particular, I want to understand the forward problem for calculating travel times of the early ray arrivals in long-range acoustic transmissions and to understand the sampling associated with those arrivals.

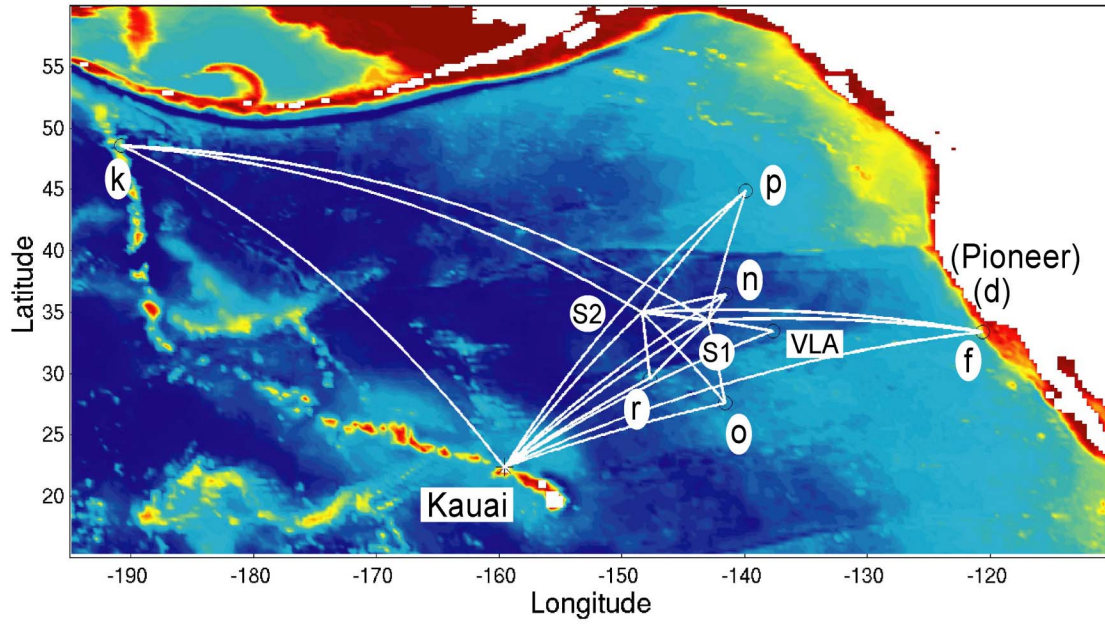
## **OBJECTIVES**

This work aims to determine the extent to which existing models of ocean variability can be used for the study of long-range acoustics. To accomplish this goal, new tools are to be developed to manage the often large size of the model output, to extract and construct the relevant acoustic properties (e.g., full-depth sections of sound speed) from the model output, and to make the acoustic calculations. Another objective is to examine data obtained on deep hydrophone arrays during the SPICEX experiment to establish general properties of receptions that occur in the shadow zone.

## **APPROACH**

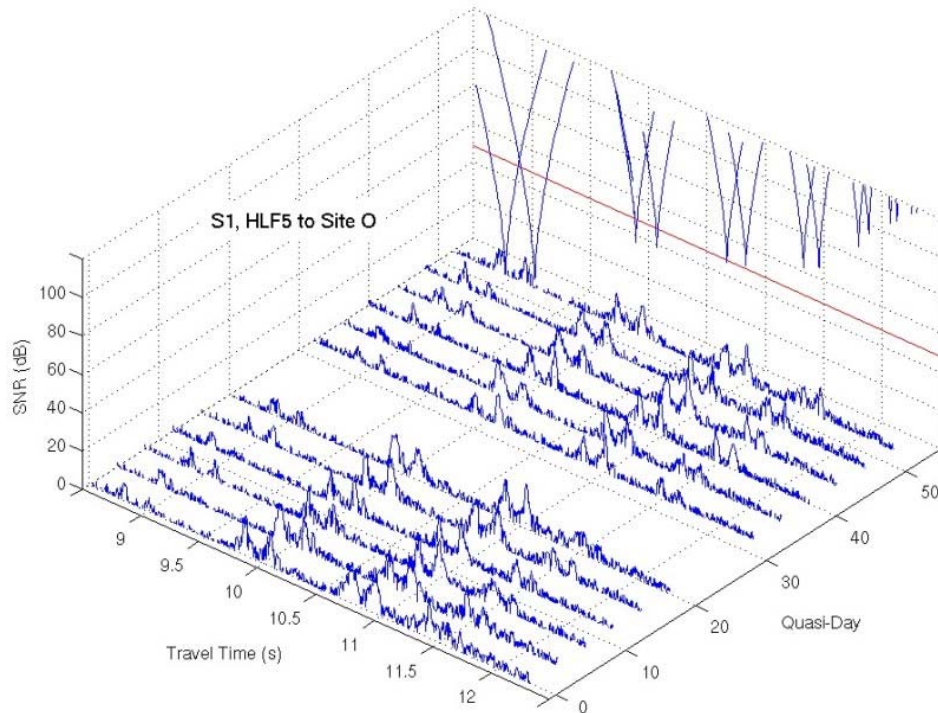
This project consists of two separate, but not entirely unrelated, investigations. First, long-range acoustic data obtained in the North Pacific during LOAPEX (Long-range Ocean Acoustic Propagation Experiment) and SPICEX (Figure 1) are to be analyzed to develop a quantified, phenomenological description of stable “ray like” arrivals measured by deep hydrophone arrays. These arrivals appear at travel times associated with the lower cusps of the acoustic time front predicted by ray calculations, but the depth of the receiver lies well below the depths of the predicted cusps (Dushaw et al. 1999) (Figure 2). The phenomenological description of these “shadow-zone” arrivals will be used to test the results from theorists and numerical modelers striving to explain the origin, and calculate the properties, of these arrivals. Second, state estimates from high-resolution ocean models for the North Pacific, e.g., 3-D fields of temperature and salinity, are to be used to examine their suitability for making accurate long-range acoustic calculations. Given the difficulty and expense of accurately characterizing the ocean environment for acoustics by data, model state estimates may eventually provide a way to obtain time-dependent acoustic environments for acoustic studies, or for accurate acoustic predictions, over long ranges. Since numerical ocean models are at present mesoscale resolving at best, it is expected

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| 14. ABSTRACT<br><b>My long-term goal is a complete and thorough understanding of the properties of acoustic pulses sent over megameter scales. In particular, I want to understand the forward problem for calculating travel times of the early ray arrivals in long-range acoustic transmissions and to understand the sampling associated with those arrivals.</b>  |                                    |                                     |   |   |                                 |
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**Figure 1. The 2004 NPAL Array.**

*[The 2004 NPAL Array consisted of three SPICEX moorings labeled S1, S2, and VLA, augmented by the 75-Hz Kauai acoustic source and SOSUS receivers denoted f, k, n, o, p, and r.]*



**Figure 2. Shadow zone receptions from NPAL source S1 to SOSUS receiver O.**

*[Shadow zone receptions from transmissions from NPAL HLF-5 source S1 (250 Hz), located near the sound channel axis, to SOSUS receiver O. Receptions over the course of two days are shown in the waterfall plot with 6 receptions per day. The prediction for the acoustic time front using rays is shown in the upper right, with the receiver depth denoted by the red line.]*

that the effects of internal waves will be modeled separately and combined with the ocean model state estimates to approximate the acoustic environment as best as possible.

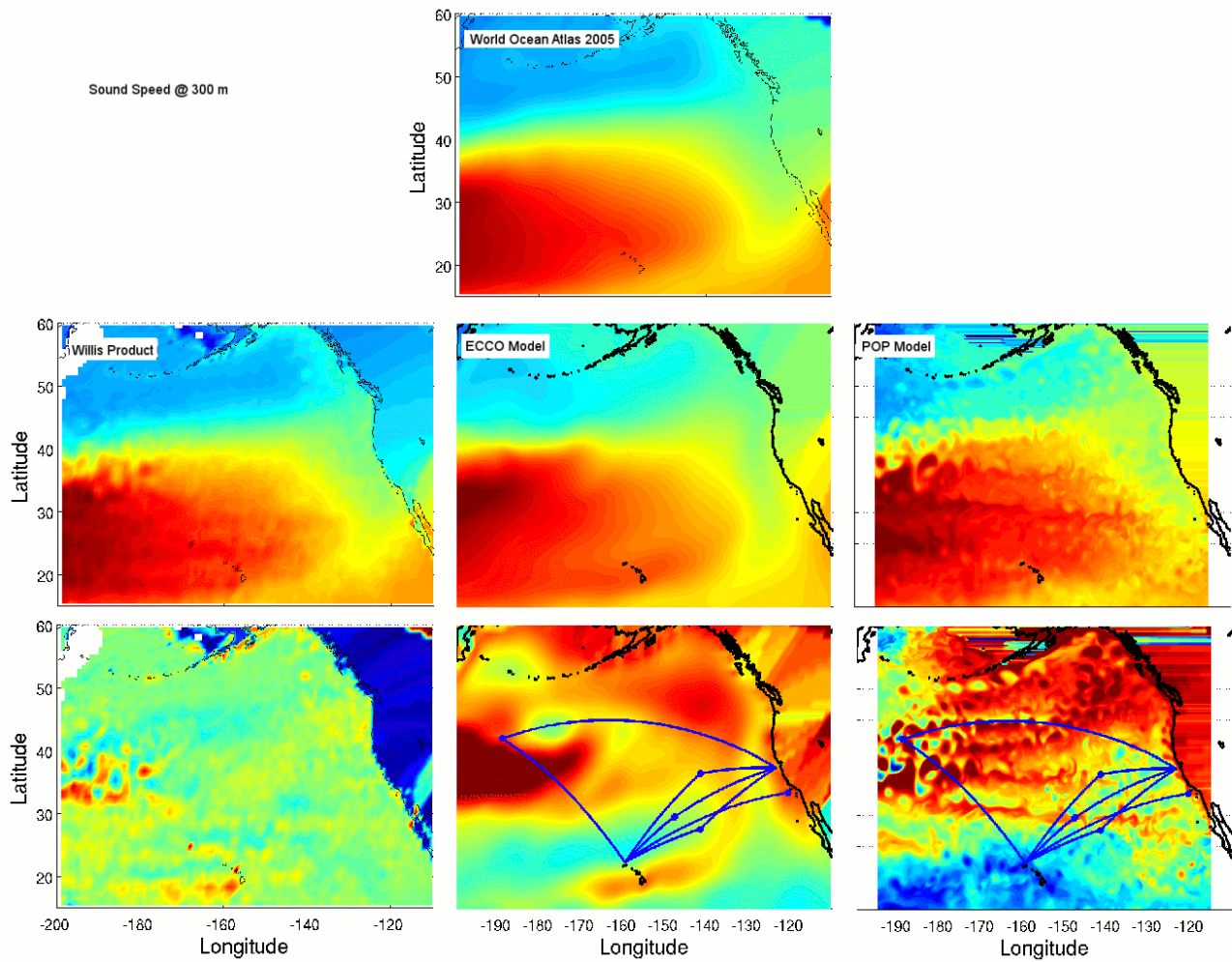
## WORK COMPLETED

This past year my work has focused on the acoustical calculations in numerical ocean models. Several models for the temperature and salinity in the North Pacific Ocean have been processed and developed so that ray tracing in them is routine. Figure 3 shows sound speed fields at 300 m calculated for four estimates of the ocean state in midwinter 2003. From simple to sophisticated, these models are:

*The 2005 World Ocean Atlas* (Locarnini et al. 2006, Antonov et al. 2006). The world ocean atlas is an important element of this work, boring though it may be, because acoustic predictions using this atlas are known to be a reasonable base state. Acoustic arrival patterns calculated with this atlas are reasonably accurate in their absolute travel time and dispersal of the multipath travel times. The atlas thus provides an important test for the acoustic accuracy of more sophisticated numerical ocean models. Sound speeds derived from the atlas can also be used to correct the time-mean state of sound speed in the models; often the time-mean state of sound speed from a model has unphysical properties. Figure 4 shows a comparison of data obtained on the Kauai source to receiver k (see Figure 1) acoustic path with ray predictions using the monthly realizations of the atlas. For this work, the ray code employed is that of Dushaw and Colosi (1998).

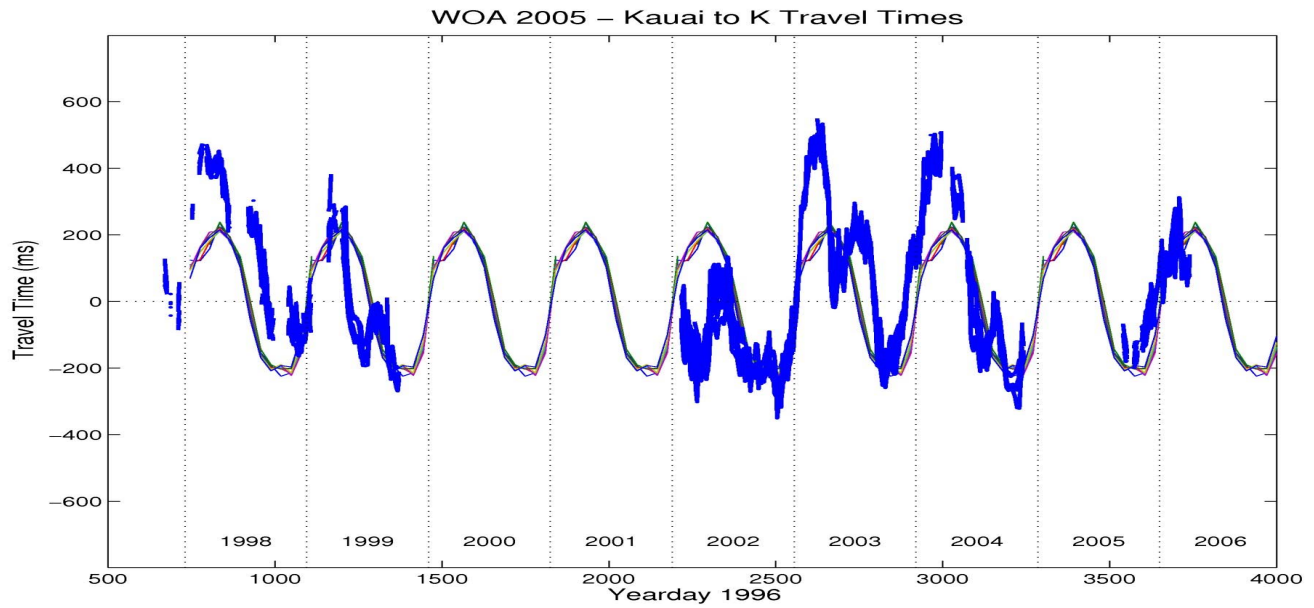
*Smoothed estimates of temperature derived from available hydrography and altimetry* (Willis et al. 2003, Willis et al. 2004). Willis et al. have calculated smoothed estimates of upper-ocean world ocean temperatures using hydrography (e.g., Argo float data) and altimetry using objective mapping techniques. These estimates have coarse resolution and are smoothed temporally with a 1-year running mean. Thus, this product does not include internal wave, mesoscale, or seasonal variability. The upper-ocean temperature profiles have been extended to the deep ocean to allow acoustic calculations using cubic spline techniques and the world ocean atlas for the abyssal values. Salinity estimates were also not yet available, salinity values were assigned using T-S relations from the World Ocean Atlas; salinity values are required to calculate sound speed.

*The “Estimating the Circulation and Climate of the Ocean” (ECCO) global ocean model* (Marshall et al. 1997a, 1997b, <http://www.ecco-group.org/>). The ECCO model is a data assimilating model that attempts to incorporate all available data (e.g., altimetry, Argo float data) to estimate the ocean state. There are various flavors of ECCO ocean models; I am using the 1-degree resolution, 46-layer model from JPL that uses a Kalman filter for data assimilation. Newer versions of this model have greater resolution, hence may provide more realistic estimates of the ocean state for acoustics. The 1-degree model suffers from a number of problems, one of which is unphysical sound speed gradients in the time-mean state. These gradients make the results of acoustic calculations rather unphysical (if not unrecognizable), so the time-mean state of the model is replaced by the World Ocean Atlas (with the model contributing estimates of the variability). I expect that any existing model will have one pathology or another in terms of its acoustic properties; working around such issues is one of the challenges of this project.

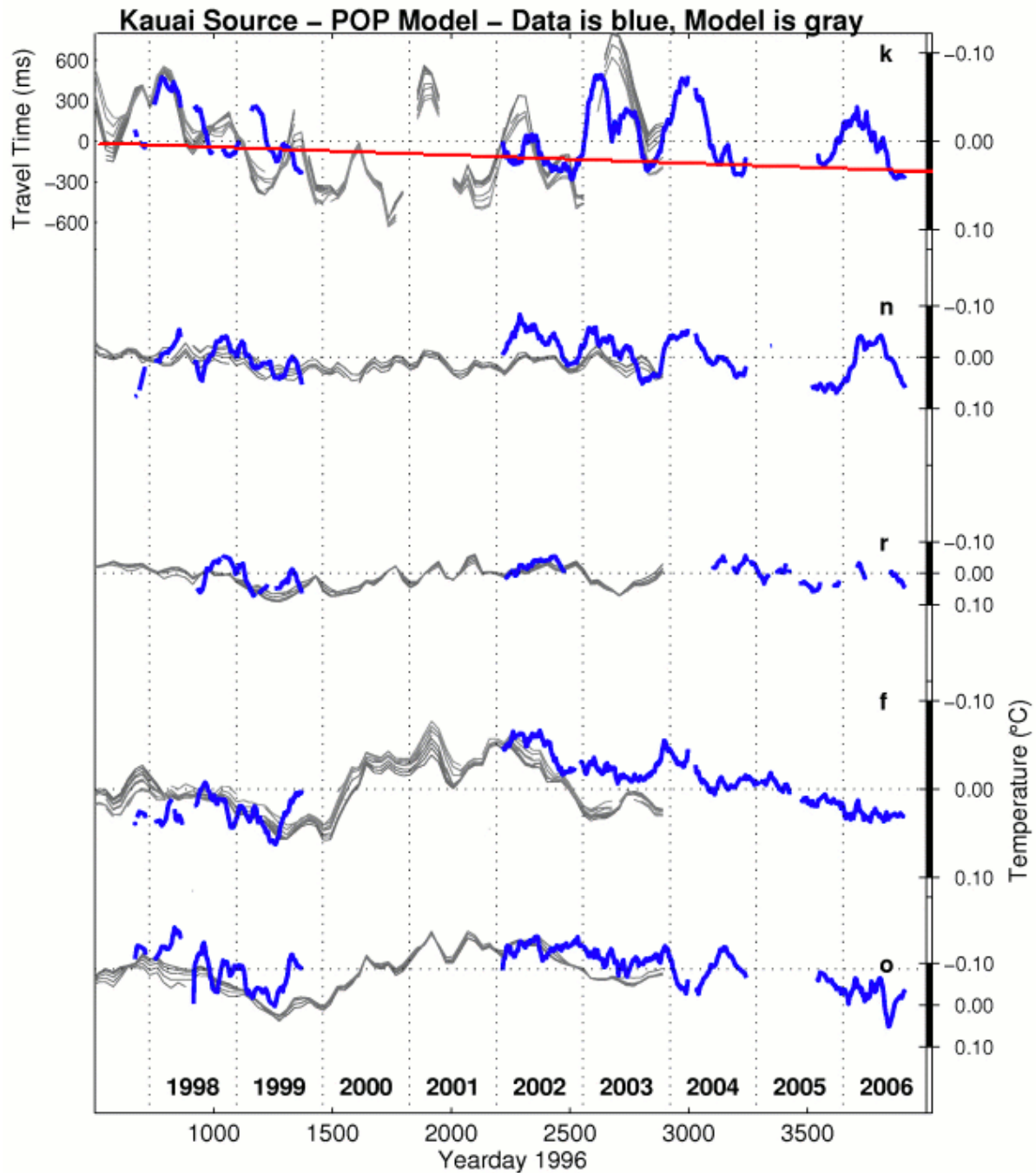


**Figure 3. A comparison of four sound speed fields of the eastern North Pacific derived from different data and analysis . [Sound speed at 300-m depth derived from four realizations of the ocean: (1) the World Ocean Atlas, (2) objective maps by Willis, (3) the ECCO model, and (4) the POP model. The three bottom realizations are all obtained for midwinter 2003. The top panels show sound speed, while the bottom panels show sound speed minus world ocean atlas, or the sound speed “anomaly”.]**





**Figure 4. Measured and Calculated Travel Times for the Kauai to k Acoustic Path.**  
*[The heavy blue lines show the measured resolved-ray travel time variability on the Kauai to “k” acoustic path. The colored lines show equivalent rays calculated using the 2005 World Ocean Atlas. Results from the 12 monthly realizations in the atlas are repeated over this 9 year duration. See also Dushaw et al. 1999.]*

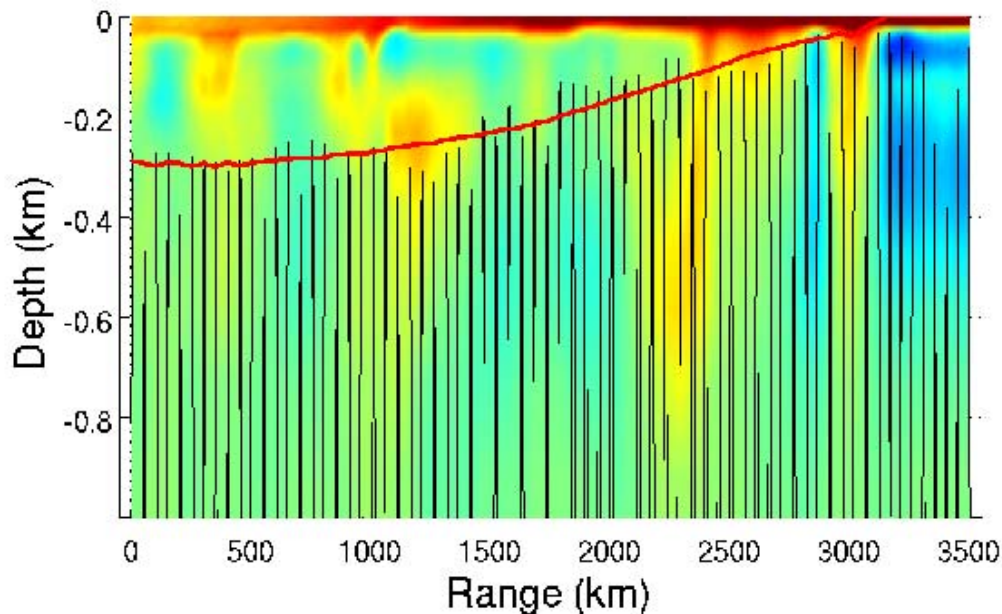


**Figure 5. Measured and Model Travel Times for Acoustic Paths from the Kauai source.** [Blue lines: the measured ray travel times for the Kauai acoustic paths. Gray lines: equivalent travel times calculated using the POP ocean model. An equivalent temperature scale is given at right. The red line in the top panel shows the expected trend corresponding to  $5 \text{ m}^\circ\text{C}/\text{yr}$  warming near the sound channel axis. This nominal number for oceanic climate change was originally suggested by Munk and Forbes (1989). The unclassified receiver locations of Figure 1, indicated on the right side of each time series, were used to perform the acoustical calculations here. ]

A high-resolution “Parallel Ocean Program” (POP) global ocean model (Maltrud and McClean 2005). J. McClean provided me with model output from her high-resolution POP model runs for the North Pacific. While this model is not data assimilating, it is driven by estimates of actual ocean forcing such as precipitation and winds, and it is mesoscale resolving. The 0.1-degree horizontal resolution and 40 depth levels of the model are ideal for acoustical calculation purposes. The model output is available monthly but continues only through 2003.

The ray travel times calculated in the POP model are compared to measured travel times in Figure 5, as an example of the sort of model testing that can be done. The calculated rays are roughly equivalent to the rays identified in the actual receptions. The calculations are to the unclassified positions shown in Figure 1. Of all the comparisons that have been made, including the Willis objective map based on Argo and altimetry and the ECCO data assimilation model, the POP model shows the most similarity to the observations. It seems clear that the acoustic data type offers unique information for testing or constraining the basin-scale temperature variations of numerical ocean models.

*Ray stability in a realistic mesoscale environment.* The POP model simulates a realistic mesoscale environment that can be used to assess the effect of the mesoscale on the ray paths. Figure 6 shows a typical ray path in one of the monthly model realizations for the Kauai to receiver k path. The upper turning points of the ray vary by 100-200 m, with similar variations in each model snapshot. Remarkably, travel times calculated with the exact rays and the world ocean atlas fixed ray differ by only several milliseconds, however. For the purposes of tomography, at least, the mesoscale influence on the ray paths is not catastrophic.



**Figure 6. A ray path calculated in the POP model for the Kauai to k Acoustic Path.**  
**[A single, identified ray path responds to the mesoscale environment of the POP model. The upper turning points of the ray vary by 100-200 m relative to the ray with the same identification derived from the smooth world ocean atlas. The red curve denotes the upper turning depths of the world ocean atlas ray. The warm temperatures of the near-surface summer mixed layer are evident. ]**



## **RESULTS**

Significant effort has been directed at manipulating the oftentimes large model data files, and merging those data with acoustic propagation capabilities. It is clear that the model results are not yet directly suitable for acoustic calculations. Constraints preserving essential acoustic properties might be a useful consideration in future model development.

Acoustic arrivals in the shadow zone were ubiquitous in the data obtained from deep receivers during the SPICEX/LOAPEX experiment. This rich data set looks as if it will be very useful for deriving general properties of this type of acoustic arrival.

The acoustic ray tracing code of Dushaw and Colosi (1998) has been developed into a subroutine that can be called by any computer code, such as a numerical ocean model during its run. For tomography and data assimilation, this tool is one of the holy grails that has not been available until now.

The comparison of measured travel times and travel times calculated in the various model estimates of the ocean state show both similarities and differences. Acoustic travel times detect oceanic variability that is not captured by the numerical models. The acoustic data type is a unique observation of large-scale temperature that can be used to correct the numerical ocean models.

## **IMPACT/APPLICATIONS**

Data-assimilating models will some day have enough resolution and data constraint that they can be used for accurate, real-time predictions of acoustic properties over any ranges anywhere in the world. This work aims to assess present capabilities, and perhaps develop criteria or constraints for better behaved acoustics that modelers can begin to implement.

The acoustical properties of shadow-zone arrivals, including the basic oceanographic and acoustical physics that give rise to them, are fundamentally not well understood. These properties are relevant to the design of deep acoustic observing systems.

The development of ray tracing code as a computer code subroutine means that numerical ocean models can now implement the basic acoustic calculations routinely. Such capability is an important step toward the routine use of long-range acoustic data for data assimilation using general circulation models.

The conclusion that the acoustic travel times offer a unique constraint of large-scale temperatures for the ocean models suggests that a long-range acoustic array might be a useful component of an ocean observing system. These results were presented at the IUGG conference held in Italy in July 2007.

## **RELATED PROJECTS**

This project is a contribution to the North Pacific Acoustic Laboratory (NPAL) collaboration, comprised of researchers from the Applied Physics Laboratory, the Scripps Institution of Oceanography, and the Massachusetts Institute of Technology, among others. (<http://npal.ucsd.edu/>)

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## HONORS/AWARDS/PRIZES

Brian D. Dushaw, Applied Physics Laboratory, University of Washington, 2007 Medwin Prize in Acoustical Oceanography from the Acoustical Society of America, “For contributions to the acoustical measurement of climate change.”